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FERMILAB-Conf-94/433

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December 1994

Presented at the *European Particle Accelerator Conference*, London, 1994.

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Increasing the Energy of the Fermilab Tevatron Accelerator

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Abstract

The superconducting Tevatron accelerator at Fermilab has reached its eleventh year of operation since being commissioned in 1983. Last summer, four significant upgrades to the cryogenic system became operational which allow Tevatron operation at higher energy. This came after many years of R&D, power testing in sectors (one sixth) of the Tevatron, and final system installation. The improvements include the addition of cold helium vapor compressors, supporting hardware for subatmospheric operation, a new satellite refrigerator control system, and a higher capacity central helium liquefier. A description of each cryogenic upgrade, commissioning experience, and attempts to increase the energy of the Tevatron are presented.

1. INTRODUCTION

The Fermilab Tevatron currently produces 900 GeV colliding beams and 800 GeV extracted beam for fixed target physics. A laboratory goal is to raise the colliding beam energy to 1000 GeV or higher. One way to achieve this is to reduce the magnet operating temperatures by about 1 K. This reduction is accomplished by pumping a mild vacuum on the magnet two-phase helium return circuits. Cold helium vapor compressors and support equipment have been added to the satellite refrigerator system in order to meet this goal. The cold compressors do work on the helium as they lower the temperature, resulting in a larger overall refrigerator heat load. This additional load is picked up by the central helium liquefier, upgraded to handle the increased burden. Subatmospheric operation requires absolute leak-tightness in the relevant helium circuits since any leaks which were formerly helium to atmosphere (a nuisance) become atmosphere to helium (a potentially catastrophic contamination event). Finally, an upgrade this extensive required the total replacement of the satellite refrigerator control system.

The upgrade was complete and ready to commission after twenty weeks of installation from June to November of 1993 (during which the Tevatron was kept at room temperature). Several weeks of testing followed in an effort to chart the Tevatron performance at lower temperature with the new hardware and software. Collider operation was demonstrated at 975 GeV, although the cryogenic system displayed some reliability problems which resulted in a

decision to postpone higher energy operation. The cryogenic system issues have since been resolved and higher energy operation will be revisited in the fall of 1994.

2. COLD COMPRESSORS

In the fall of 1992 Fermilab took delivery of 27 centrifugal cold helium vapor compressors manufactured by IHI Co., Ltd. of Japan. One of these compact, dynamic gas bearing turbomachines resides in each of our 24 satellite refrigerators; the remaining three are spares. A detailed description of these units is found elsewhere [1]. These compressors have successfully lowered the operating temperature of the Tevatron magnets by about 0.7 K. This has translated into an increase in maximum beam energy from 935 to 975 GeV, a smaller increase than anticipated by short sample testing of the superconductor. Compressor operation was less than totally reliable during Tevatron startup and higher energy testing. Problems included stuck compressor shafts caused by contamination, excessive pressure drop caused by an overly restrictive intake filter (subsequently removed), and poorly tuned control loops which caused overload trips due to rapid shaft acceleration. These findings are described in references [2] and [3].

After several study periods of one or two day duration, these bugs were worked out and compressor operation is meeting expectations. However, the current physics run is being conducted at 900 GeV, without cold compressors, because the reliability issues were not addressed prior to the start of physics commissioning in January 1994. Since then we have operated compressors five at a time to gain experience and take performance data. To date we have over 24,000 total operating hours with only one compressor failure (a defective rotor which failed after less than one hour of operation).

3. SUBATMOSPHERIC HARDWARE

Tevatron operation above about 940 GeV means pulling a vacuum at the inlet to the cold compressor, which communicates with the two-phase circuit of the magnet strings. This requires hermetic seals at all interfaces between the two-phase circuit and the atmosphere. We were therefore required to upgrade 250 magnet relief valves and 50 control valves in place as well as provide for additional hermetic connections on new equipment [4]. Metal seals were used wherever possible; elsewhere, double elastomer O-rings with guard helium were used. We have had no contamination problems since Tevatron cooldown in November 1993.

¹ Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000

4. CONTROL SYSTEM

The original satellite refrigerator controls hardware had insufficient expansion available to meet the needs of the cryogenics upgrade; for example, I/O terminations are increased by a factor of two in the new system. There is also a need for greater control loop capacity and intelligent control algorithms which the old system could not provide. As a consequence, the entire satellite refrigerator control system has been upgraded with an Intel 80386-based, Multibus II package.

Each satellite refrigerator and compressor location (24 and 8 sites, respectively) is controlled by a dedicated 386 processor. All processors for a sector (one sixth) of the Tevatron are housed in a single crate. Sectors communicate with each other and with the ACNET accelerator control system via Token Ring. Ethernet is also supported for performing diagnostics and initialization. Within each sector, the independent 386 processors communicate over an Arcnet LAN with two Intel 186 local processors. One controls device I/O for transducers, valves, digital devices, and motors for rotating machinery. The other serves the carbon and platinum resistance thermometry for that location. The compressor locations do not use this second 186 board since there is no pulsed current resistance thermometry there.

Software capabilities are significantly enhanced over the original system. PID control loops are supported for 32 devices, up from 20 (24 of these slots are currently filled.) Programmed control of each location is accomplished by finite state machine software. Thirty-two separate machines (each containing sixteen states) are available for automatic cool down, quench recovery, intelligent adjustment of loop parameters, protection of rotating machinery, etc. Seventeen finite state machines are currently used at each refrigerator. The new control system should provide ample capacity for future upgrades. Details of this system are provided in reference [5].

5. CENTRAL HELIUM LIQUEFIER

Satellite refrigerator simulation suggested that the existing capacity at the central helium liquefier (CHL) would be insufficient to meet the demands imposed by lower temperature, higher energy operation. A cold compressor adds upwards of 400 watts to the satellite refrigerator heat load with a 3.6 K inlet and about 6 K exhaust at 40 grams/sec. This extra load is removed almost exclusively by the CHL via additional liquid helium from the transfer line at each satellite location. Thus the upgrade boosts the nominal CHL output requirement from 120 to 170 grams/sec. This exceeds the capacity of the original cold box. Fortunately, the planned upgrade of CHL included a "redundant" cold box with 35% greater capacity through the use of larger expansion turbines. The new cold box meets the needs of the lower temperature upgrade although the original goal of the CHL enhancement (increased reliability via redundant cold boxes) had to be abandoned. Future plans call for capacity improvements to the original cold box as well as compressor upgrades.

The new cold box uses heat exchangers and flow paths

identical to the old cold box. Capacity is improved by using higher flow expanders. These units are oil bearing, oil braked turbomachines with variable area inlet nozzles. This provides efficient turn-down capability when full output is not required (when cold compressors are off, for example). The new cold box has been measured at 179 grams/sec output with 90% of rated flow.

A fourth reciprocating helium compressor is being added in support of the CHL upgrade. The unit is a converted Worthington air compressor similar to the originals except that it has been re-staged for 40% greater throughput. Additional information on the CHL upgrades can be found in reference [6].

6. COMMISSIONING EXPERIENCE

The Tevatron was at 4.5 K by November 9, 1993 following the installation of all aspects of the lower temperature upgrade. Prior to the cooldown, the new control system was extensively tested and debugged with the exception of the new finite state machines. There was no way to test these algorithms prior to their actual use for automatic cooldown, quench recovery, etc. Cold compressors had been acceptance tested on room temperature air upon receipt. Prior to ring-wide cooldown, a single cold compressor was installed and that location cooled to 4.5 K to get some early experience with the new system. This testing time proved valuable in that the "stuck shaft" problem discussed in Section 2 was uncovered; also, significant tuning of the control loops and finite state machine debugging took place.

The first round of quench testing began in December of 1993. These tests were designed to discover the new energy limit of the Tevatron while at lower temperature. The limit of CHL's new cold box was reached after a magnet temperature reduction of only 0.5 K; this was clear evidence that the cold compressors were running with poor efficiency (borne out by specific measurements). The solution was to remove the improperly sized intake filter. Thereafter, the compressor performance was within the specification, allowing temperature reductions of 0.7 K. A second round of quench testing took place following filter removal. A great deal of tuning, debugging, and training occurred during this period. References [2] and [3] describe the commissioning experience in greater detail.

7. INCREASING THE ENERGY

Without cold compressors the Tevatron operates 900 GeV colliding beams. Data from short samples of the magnet conductor indicate that peak current increases linearly with decreasing temperature at the rate of 15% per degree K. Earlier quench tests in isolated sectors of the Tevatron [7] suggested that this performance could be reasonably expected from the installed magnets (after training quenches). The first round of quench testing resulted in a peak field corresponding to a beam energy of 997 GeV. This was a reasonable result given the poor cold compressor performance and resulting magnet temperatures. However,

this energy was reached only after nine training quenches, each generally occurring at progressively higher energy and at shifting locations in the ring. The ultimate energy was not identified by repeated quenches of a particular magnet; rather, the quenching continued to shift location but without any corresponding increase in energy. This may suggest some widespread, common limit in a substantial portion of the Tevatron magnets. Some test results are shown in Figure 1.

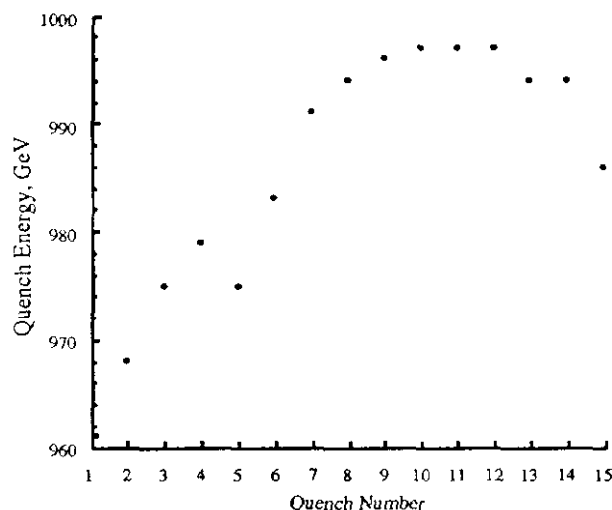


Figure 1. Results of the first round of quench testing.

The second round of quench testing took place at lower temperatures thanks to improved cold compressor performance. The tests focused less on reaching maximum energy and more on duplicating actual collider physics operation at lower temperature. During these tests the cold compressors displayed operational instabilities. This perceived lack of reliability factored heavily in the subsequent decision to conduct the following physics run at the previous (pre-upgrade) energy of 900 GeV. The second round resulted in a demonstrated physics capability at 975 GeV, limited by quenches in the special "low beta" magnets at the B0 interaction region. These magnets had not been powered during the first round of testing.

8. CONCLUSIONS

Efforts to increase the energy of the Tevatron have not achieved the goal of reliable 1 TeV collider operation; however, the lower temperature upgrade (the cryogenics part) has been successful in lowering the operating temperature of the Tevatron by the prescribed amount. There is clearly a need for additional lower temperature quench testing and perhaps weak component replacement if we are to reach our energy goal.

The cryogenic system upgrade has been a relatively painless success, given the extent of the work and the very tight installation schedule. The new controls hardware has been extremely reliable (causing zero recorded accelerator

downtime in the six months of the current physics run). Likewise, the software has performed as advertised. There are no contamination issues associated with prolonged subatmospheric operation – a major worry from the beginning. With the exception of some commissioning and infancy failures, CHL has operated the new cold box without incident. The IHI cold compressors are doing their job and have over 24,000 cumulative hours of operation with only one (infancy) failure. Overall reliability has improved as we learn the new system. Downtime for cryogenics would be proportionately less for this run as compared to the last were it not for a rash of wet expander main shaft failures. This problem may be solved by using tougher material and surface treatment.

Achievement of 1 TeV is proving to be a greater challenge than simply lowering the operating temperature. The sector tests described in reference [7] suggested that the magnets would generally follow the short sample behavior of the conductor. At least, three of six Tevatron sectors more or less did so when tested independently. The ring wide quench testing showed that even these previously tested sectors did not behave as they had when tested alone. Additional power tests are required to understand the magnet performance and to isolate the weakest magnets.

9. REFERENCES

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